What can we do if we do not find a Higgs?

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If we do not find a Higgs either

- it is too heavy.
- it does not exist (but some alternative physics should be there)

We need a predictive approach to deal with the Symmetry Breaking Sector (SBS) up to LHC energies, which should be

- Systematic: to obtain all observables with an organized procedure to calculate quantum corrections in a model independent way.
- Consistent: Finite results. $SU(2)_L \times U(1)_Y$ gauge invariant, unitary ...

This is achieved with the Electroweak Effective Chiral Lagrangian (EChL) formalism.

The EChL is written in terms of the standard fields, $W^{\pm}, Z^0, \gamma ...$ as well as

- 3 Goldstone Bosons, because $W^{\pm}, Z^0$ massive. They drive the spontaneous $SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$ breaking.
- a breaking scale $v \simeq 246$ GeV.
- a soft $SU(2)_C$ breaking ($\sim g'$) because $\rho \simeq 1$

and it should respect the bounds from LEP and Tevatron.

FOUR MAIN IDEAS

1. If there is no Higgs or other light resonances:

   $$\Downarrow$$

   SBS at low energy = Goldstone Boson Dynamics

2. Chiral Symmetry Breaking determines low-energy dynamics.

   $$\Downarrow$$

   Universal Low Energy Theorems
   (like Current Algebra in QCD)

   $$t(s,t,u) \simeq \frac{s}{A_I}$$

3. SBS interactions become STRONG around 1 TeV.

4. Intuitively: Gauge bosons $\simeq$ Longitudinal gauge bosons
   Equivalence Theorem (ET):

   $$T(V_L, V_L, ..., \Phi) = T(\omega, \omega, ..., \Phi) + \mathcal{O}\left(\frac{M}{\sqrt{s}}\right)$$

   - We expect an enhancement of V_L's
   - With longitudinal gauge bosons we test the SBS

The Electroweak SBS Effective Chiral Lagrangian

(Appelquist, Bernard, Longhitano)

The 3 GB's can be parametrized in an $SU(2)$ matrix:

$$U = \exp\left(\frac{i\omega^a\sigma^a}{v}\right)$$

Since we only know the light modes of the SBS, its lagrangian is a low-energy (derivative) expansion. The dimension 2 term

$$\mathcal{L}^{(2)} = \frac{v^2}{4}\mathrm{tr} D_\mu U D^\mu U^\dagger$$

yields the Low Energy Theorems ($A(s) = s/v2$), in addition we have

$$\begin{aligned}
\mathcal{L}'^{(2)} &= a_0\frac{g'^2v^2}{4}[\mathrm{tr}(TV_\nu)]^2 \\
\mathcal{L}^{(4)} &= a_1\frac{igg'}{2}B_{\mu\nu}\mathrm{tr}(TF^{\mu\nu}) + a_2\frac{ig'}{2}B_{\mu\nu}\mathrm{tr}(T[V^\mu, V^\nu]) \\
&+ a_3 g\mathrm{tr}(F_{\mu\nu}[V^\mu, V^\nu]) + a_4[\mathrm{tr}(V_\mu V_\nu)]^2 \\
&+ a_5[\mathrm{tr}(V_\mu V^\mu)]^2 + a_6\mathrm{tr}(V_\mu V_\nu)\mathrm{tr}(TV^\mu)\mathrm{tr}(TV^\nu) \\
&+ a_7\mathrm{tr}(V_\mu V^\mu)[\mathrm{tr}(TV^\nu)]^2 + a_8\frac{g^2}{4}[\mathrm{tr}(TF_{\mu\nu})]^2 \\
&+ a_9\frac{g}{2}\mathrm{tr}(TF_{\mu\nu})\mathrm{tr}(T[V^\mu, V^\nu]) + a_{10}[\mathrm{tr}(TV_\mu)\mathrm{tr}(TV_\nu)]^2 \\
&+ g a_{11}\epsilon^{\mu\nu\rho\sigma}\mathrm{tr}\left(TV_\mu\right)\mathrm{tr}\left(TV_\nu F_{\rho\sigma}\right) \\
&+ \text{e.o.m. terms} + \text{non-CP terms}
\end{aligned}$$

$$T = U\tau^3U^\dagger \quad ; \quad V_\mu = (D_\mu U)\,U^\dagger$$

The a parameters:

- absorb the one-loop divergences from $\mathcal{L}^{(2)}$.

$$\Downarrow$$

Finite results to D=4.

- once renormalized they parameterize our ignorance on the SBS.

$$\Downarrow$$

Different a's $\Longleftrightarrow$ different models.

This procedure can be carried out to any desired order.

Toy Models

- SM Heavy Higgs limit: M.J. Herrero, E. Ruiz-Morales

$$a_0(\mu)=\frac{1}{16\pi^2}\frac{3}{8}\left(\frac{5}{6}-\log\frac{M_H^2}{\mu^2}\right) \quad a_3(\mu)=\frac{-1}{16\pi^2}\frac{1}{24}\left(\frac{17}{6}-\log\frac{M_H^2}{\mu^2}\right)$$

$$a_1(\mu)=\frac{1}{16\pi^2}\frac{1}{12}\left(\frac{5}{6}-\log\frac{M_H^2}{\mu^2}\right) \quad a_4(\mu)=\frac{-1}{16\pi^2}\frac{1}{12}\left(\frac{17}{6}-\log\frac{M_H^2}{\mu^2}\right)$$

$$a_2(\mu)=\frac{1}{16\pi^2}\frac{1}{24}\left(\frac{17}{6}-\log\frac{M_H^2}{\mu^2}\right)$$

$$a_5(\mu)=\frac{v^2}{8M_H^2}-\frac{1}{16\pi^2}\frac{1}{24}\left(\frac{79}{3}-\frac{27\pi}{2\sqrt{3}}-\log\frac{M_H^2}{\mu^2}\right)$$

- Rescaled Large-N QCD: T.Appelquist, G.-H. Wu

$$a_1=a_2=-a_3=-2a_4=4a_5=-N_{TC}/96\pi^2$$

Ours	App.& Longh.	S.Dawson	He et al.	Vertex	Breaks
a_0	$\frac{g^2}{g'^2}\beta_1$	$\frac{1}{g'^2}\beta_1$	$\frac{1}{16\pi^2}\frac{1}{g'^2}l_0$	2	$SU(2)_c$
a_1	$\frac{g}{g'}\alpha_1$	α_1	$\frac{1}{16\pi^2}l_1$	2,3	$SU(2)_c$
a_2	$\frac{g}{g'}\alpha_2$	α_2	$\frac{1}{16\pi^2}l_2$	3	$SU(2)_c$
a_3	$-\alpha_3$	$-\alpha_3$	$\frac{-1}{16\pi^2}l_3$	3,4	
a_4	α_4	α_4	$\frac{1}{16\pi^2}l_4$	4	
a_5	α_5	α_5	$\frac{1}{16\pi^2}l_5$	4	
a_6	α_6	α_6	$\frac{1}{16\pi^2}l_6$	4	$SU(2)_c$
a_7	α_7	α_7	$\frac{1}{16\pi^2}l_7$	4	$SU(2)_c$
a_8	$-\alpha_8$	$-\alpha_8$	$\frac{-1}{16\pi^2}l_8$	2,3,4	$SU(2)_c$
a_9	$-\alpha_9$	$-\alpha_9$	$\frac{-1}{16\pi^2}l_9$	3,4	$SU(2)_c$
a_{10}	$\frac{1}{2}\alpha_{10}$	$\frac{1}{2}\alpha_{10}$	$\frac{-1}{16\pi^2}\frac{1}{2}l_{10}$	4	$SU(2)_c$

By dimensional analysis we expect them to be 10^{-2} to 10^{-3}

Present Bounds

Two point functions

We have

$$S = 16\pi\,[-a_1(\mu) + \text{EChL loops}(\mu)]$$
$$T = \frac{8\pi}{c_W^2}\,[a_0(\mu) + \text{EChL loops}(\mu)]$$
$$U = 16\pi\,[a_8(\mu) + \text{EChL loops}(\mu)]$$

A. Dobado, D. Espriu and M.J. Herrero

Using PDG 1998

$$\Delta S = -0.26 \pm 0.14$$
$$\Delta T = -0.11 \pm 0.16$$
$$\Delta U = 0.26 \pm 0.24$$

for $M_H = 300\,\text{GeV}$ and $m_t = 175 \pm 5\,\text{GeV}$ at 1 σ, we get

$$a_1(1\text{TeV}) = (6.8 \pm 2.8) \times 10^{-3}$$
$$a_0(1\text{TeV}) = (4.3 \pm 4.9) \times 10^{-3}$$
$$a_8(1\text{TeV}) = (4.9 \pm 4.7) \times 10^{-3}$$

Other studies agree within errors. Dawson , Valencia and Alan,Dawson,Szalapski

Present Bounds

Three point functions

We have

$$
\begin{aligned}
g_1^\gamma - 1 &= 0 + \text{EChL loops} \\
g_1^Z - 1 &= \frac{-g^2}{c_W^2} a_3 + \text{EChL loops} \\
\kappa_\gamma - 1 &= g^2(a_2 - a_3 - a_1 + a_8 - a_9) + \text{EChL loops} \\
\kappa_Z - 1 &= g^2(a_8 - a_3 - a_9) + g'^2(a_1 - a_2) + \text{EChL loops} \\
\lambda_\gamma &= 0 \quad \lambda_Z = 0
\end{aligned}
$$

The EChL loop effects are $\sim 10^{-3}$. D.Espriu and M.J. Herrero
From present 1σ bounds from LEP+Tevatron:
Dean Karlen, ICHEP 98 Plenary talk, Vancouver

$$
\begin{aligned}
\kappa_\gamma - 1 &= 0.13 \pm 0.14 \\
g_1^Z - 1 &= 0.00 \pm 0.08 \\
\lambda_\gamma = &- 0.03 \pm 0.07
\end{aligned}
$$

$$
a_2 - a_3 - a_1 + a_8 - a_9 = 0.30 \pm 0.33
$$
$$
a_3 = 0.00 \pm 0.14
$$

Quartic couplings*

$$
-0.160 < a_4 < 0.054 \;,\; -0.410 < a_5 < 0.013
$$
$$
-0.027 < a_6 < 0.009 \;,\; -0.026 < a_7 < 0.009
$$
$$
-0.014 < a_{10} < 0.0045
$$

* Higher order incomplete chiral calculation + LEP data.

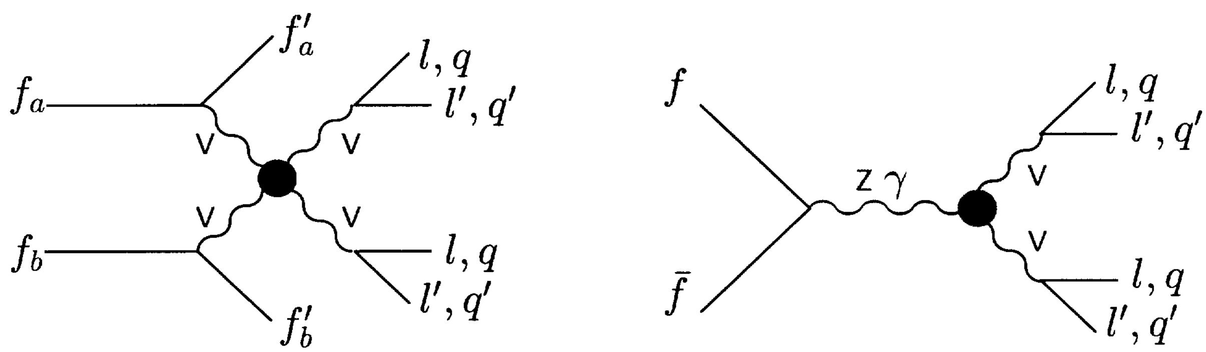
From A.S.Belyaev et al. hep-ph/9805229

LHC Prospects

The absence of a light Higgs or other light resonances implies that around 1 TeV the SBS interactions become strong.

The most characteristic signal is an enhancement in longitudinal gauge bosons in

Fusion (Genuine SBS) Annihilation



Limited by background.

Only Gold-plated modes studied.

- Isolated high p_T leptons.
- $\not{E}_T$
- No central jet activity.

Crucial:

- Central jet veto.
- Forward jet tagging.

Experiments are hard. Need ultimate $\sqrt{s}$ and full $\mathcal{L}$.
LHC $\sqrt{s} = 14$ TeV, 100 fb^{-1}/detector-year

LHC bounds in non-resonant studies

Study for CMS Technical Proposal

CERN/LHC94-38.LHCC/P1.(1994)

A.Dobado, M.T. Urdiales and A.Dobado et al. *Phys.Lett.B352*(1995)400.

Number of Events and Statistical Significances

	a_4				a_5			
	10^{-2}	-10^{-2}	$5\,10^{-3}$	$-5\,10^{-3}$	10^{-2}	-10^{-2}	$5\,10^{-3}$	$-5\,10^{-3}$
$W^\pm Z \to W^\pm Z$	36	80	27	47	22	58	23	41
total $W^\pm Z$	118	162	109	129	104	139	105	122
$r_{W\,Z}$	0.7	4.8	0.2	1.7	0.7	2.6	0.6	1.0
$r_{W\,tagging}$	1.0	7.5	0.3	2.7	1.0	4.2	0.9	1.7
$W^+W^- \to ZZ$	12	7	9	7	21	7	13	6
$ZZ \to ZZ$	6	6	1	1	6	6	1	1
total ZZ	37	32	30	27	46	32	33	26
r_{ZZ}	1.9	0.9	0.5	$\simeq 0$	3.8	0.9	1.2	0.1
$r_{ZZ\,tagging}$	3.5	1.8	0.9	0.1	6.6	1.8	2.3	0.2

	a_3	
	10^{-2}	-10^{-2}
$qq' \to W^\pm Z$	96	139
$r_{WZ\,tagging}$	1.4	2.7

Without the EWA

From A.S.Belyaev et al. hep-ph/9805229

LHC Limits (90% CL)	Process
$-0.0035 \leq a_4 \leq 0.015$	$W^\pm W^\pm, WZ, ZZ$
$-0.0072 \leq a_5 \leq 0.013$	$W^\pm W^\pm, WZ, ZZ$
$-0.013 \leq a_6 \leq 0.013$	WZ, ZZ
$-0.013 \leq a_7 \leq 0.011$	WZ, ZZ
$-0.029 \leq a_{10} \leq 0.029$	ZZ

UNITARITY AND RESONANCES

- Elastic unitarity requires

$$\text{Im}\, t = \sigma |t|^2 \qquad \text{(Optical Theorem)}$$

where σ is the known phase-space factor.

- Chiral amplitudes are an energy expansion $t = t_2 + t_4 + \dots$. They only satisfy unitarity perturbatively.

Non-resonant studies have to be interpreted cautiously. The violation can be severe around 1 to 3 TeV if $|a_i| > 0.005$.

- We expect RESONANCES !!! (to fix unitarity)

- Unitarity and resonances can be easily implemented in the ECHL formalism, since

$$\text{Im}\, t^{-1} = -\frac{\text{Im} t}{|t|^2} = -\sigma \quad \Rightarrow \quad t^{-1} = \text{Re}\, t^{-1} - i\,\sigma$$

$$\text{Thus} \quad t = \frac{1}{\text{Re}\, t^{-1} - i\,\sigma} \qquad \text{Expand only Re}\, t^{-1}\text{!!!}$$

Different unitarization procedures are different approximations to Re t^{-1}. If we expand t to $\mathcal{O}(p^4)$ within the ECHL we get the Inverse Amplitude Method.

Testing the Inverse Amplitude Method

- We can test the inverse amplitude method with data, since the Equivalence Theorem tells us that:

$$V_L \text{ scattering} \simeq \text{Goldstone boson scattering}$$

  and we have a similar theory and data for pions.

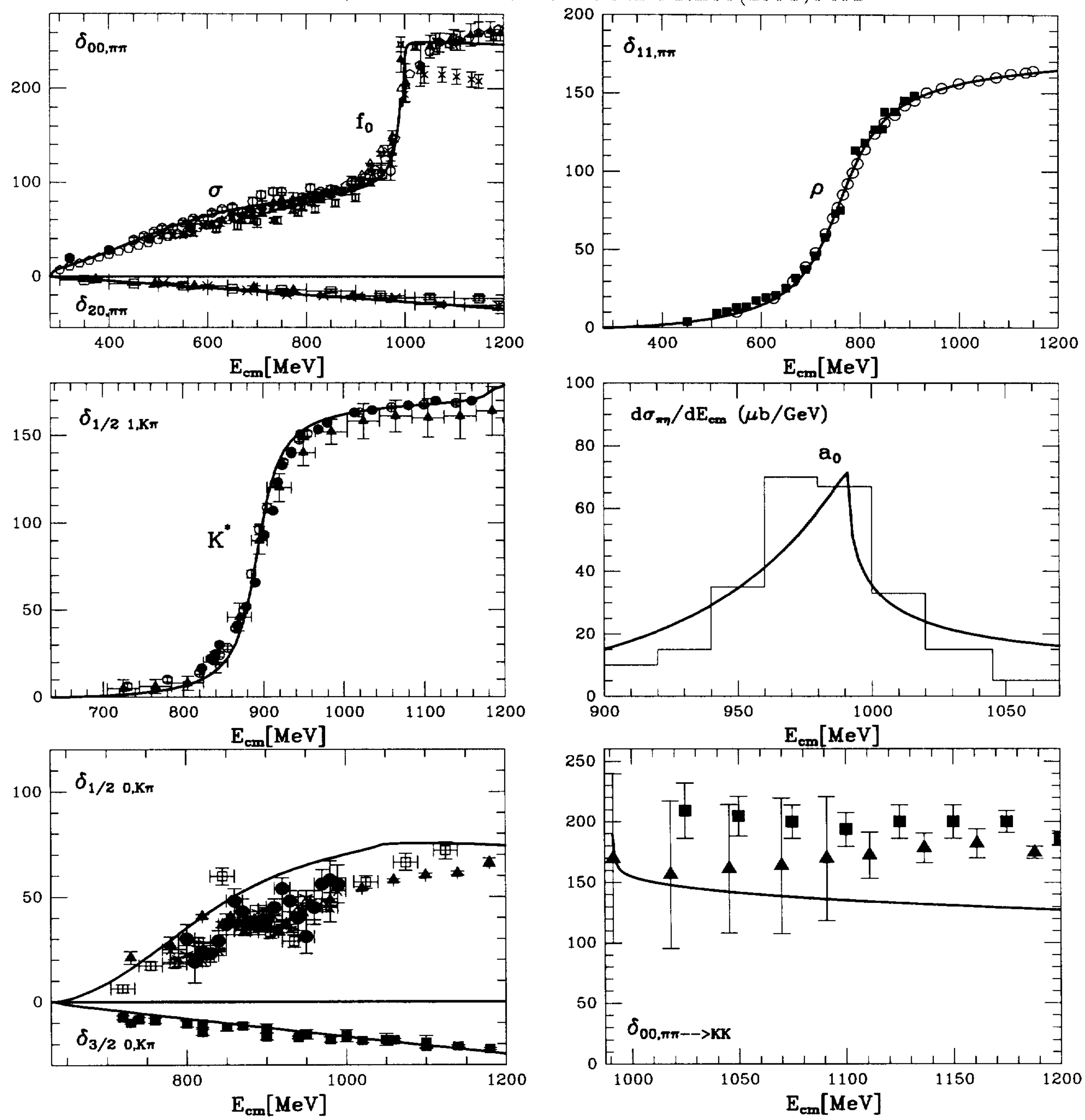
- In $\pi\pi$ scattering we also have $SU(2)_L \times SU(2)_R \longrightarrow SU(2)_{L+R}$ and a similar Lagrangian scaled from:

$$\begin{aligned} 4\pi v &\simeq 3 \text{ TeV} \\ &\downarrow \\ 4\pi f_\pi &\simeq 1 \text{ GeV} \end{aligned}$$

- For πK scattering we have $SU(3)_L \times SU(3)_R \longrightarrow SU(3)_{L+R}$ and one parameter more.

The Inverse amplitude Method in meson scattering

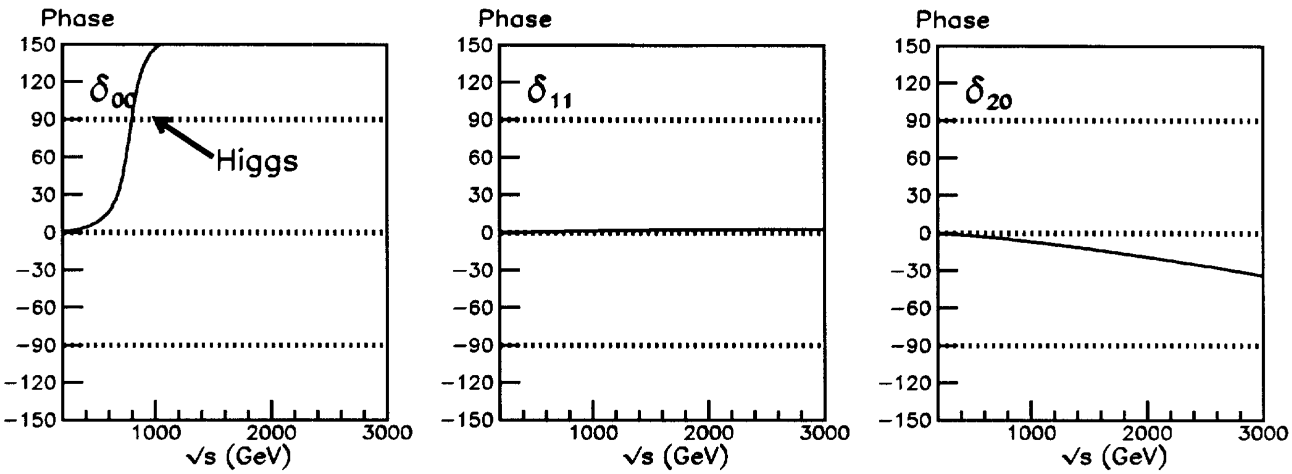
J.A. Oller, E. Oset and J. R. Peláez PRL80(1998)3452



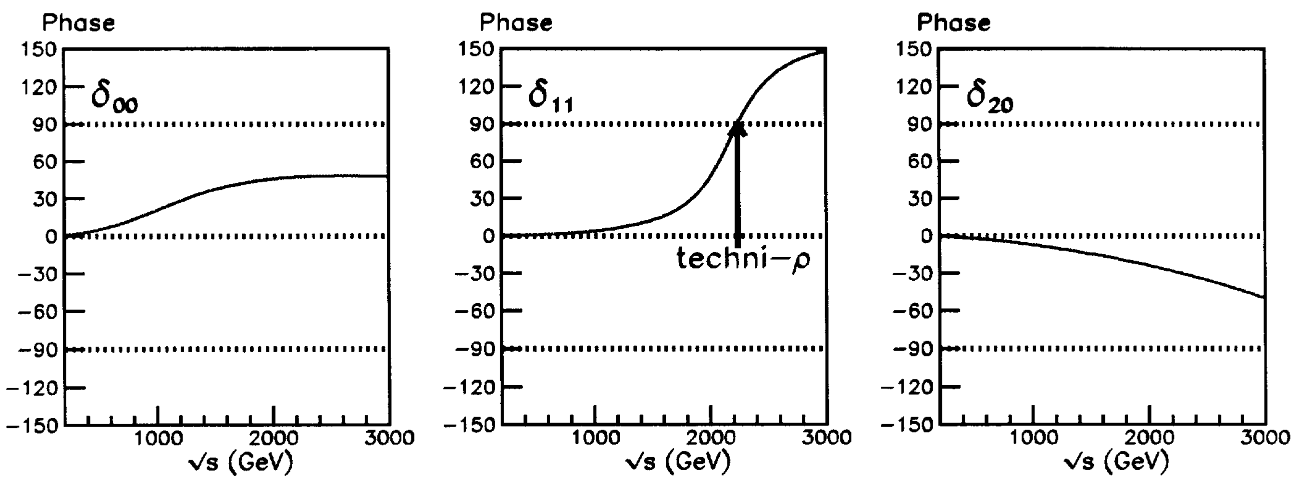
Results of the IAM for the phase shifts of $\pi\pi$ scattering in the $(I,J) = (0,0),(1,1),(2,0)$ channels, where the σ, f_0 and ρ resonances appear, together with those of $\pi\pi \to K\bar{K}$, as well as the phase shifts of πK scattering in the $(3/2,0),(1/2,0)$ and $(1/2,1)$ channels, where we can see the appearance of the K^* resonance. The results also include the $\pi^-\eta$ mass distribution for the a_0 resonance in the $(I,J)=(1,0)$ channel from $K^-p \to \Sigma(1385)\pi^-\eta$.

Phase shifts in Strong $V_LV_L \rightarrow V_LV_L$ Scattering

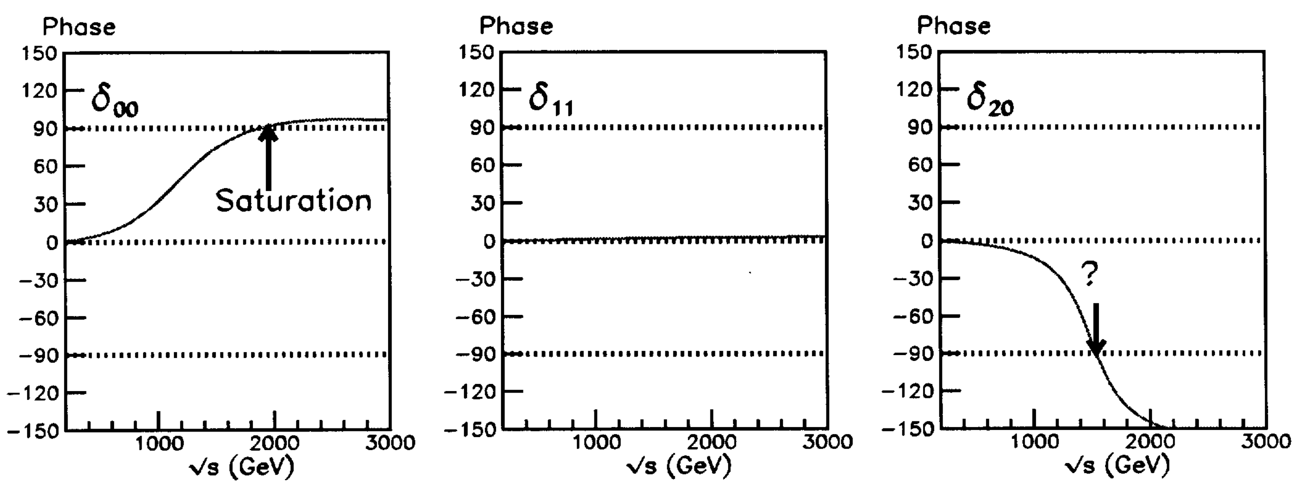
- Heavy Higgs MSM



- QCD−like



- I=2 Resonance Model



Resonances at LHC with the Unitarized EChL

LHC Achen Workshop (1990):

Study with old LHC parameters EWA + ET.

- Only Higgs-like and ρ-like studied for particular choice of parameters in Gold-plated models. No tagging
- Conclusions:

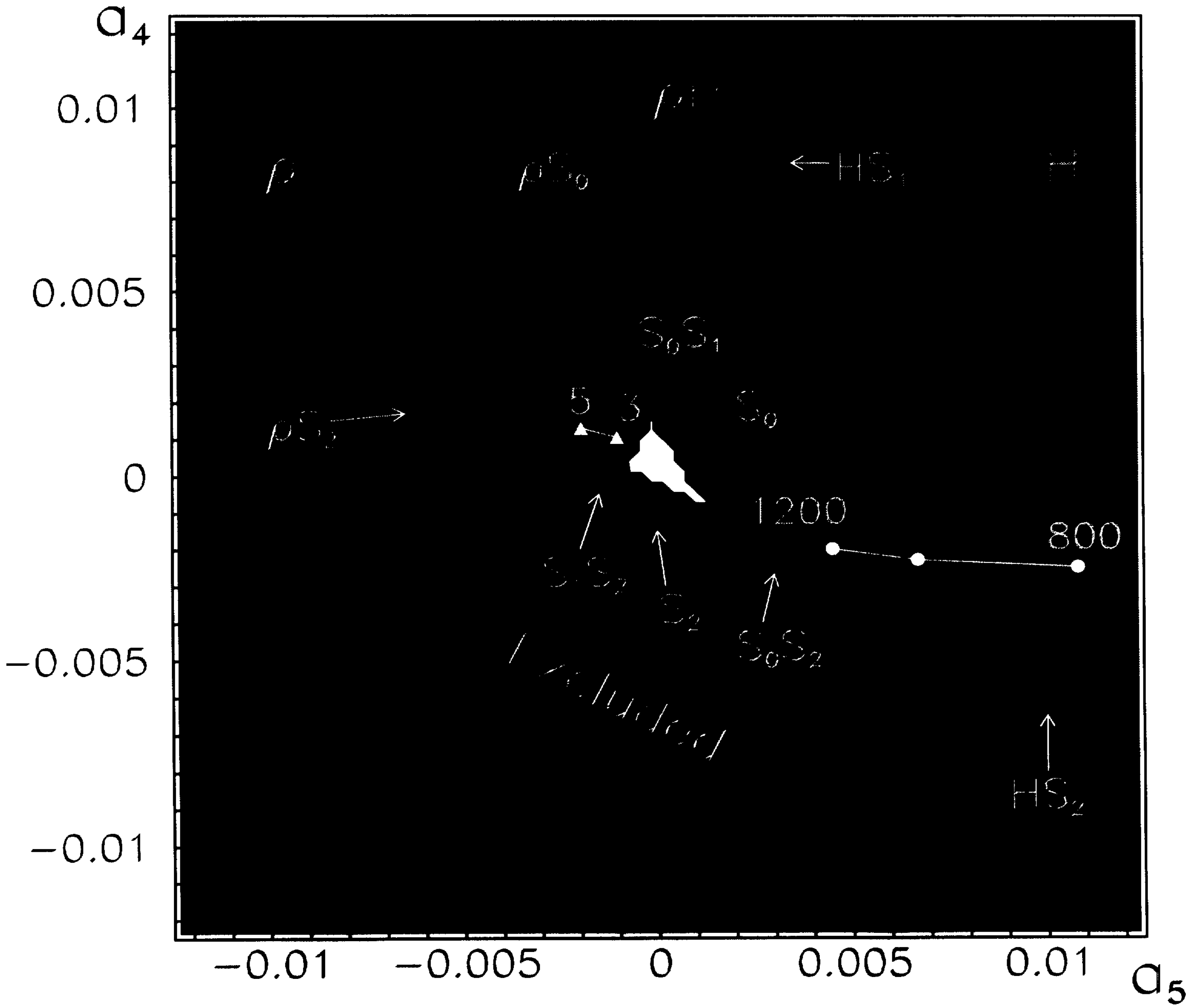
  - ρ-like up to 2 TeV identifiable in WZ channel.

  - 1 TeV scalar resonance hard to disentangle (only ZZ studied)

Lots of room for improvement!!!

General Resonance Spectrum of the strong SBS

J.R.Peláez, PRD55(1997)4193



Conclusions

- The EChL provide an appropriate formalism to study in a model independent way the strongly interacting SBS.
- Provides a systematic and consistent approach. It can also implement easily unitarity and resonances.

LHC Prospects within the ECHL

- Top and like-sign channels: W^+W^+ and W^-W^-.
- Multichannel analysis.
- Hadronic decays, statistical V_T V_L separation, detector simulations: tagging, veto, efficiencies, double tag, pile-up, optimal cuts...
- Update experimental resonance search studies for all parameter space.
- Unitarization of coupled channels: transverse Vs, initial states like qq', V multiproduction.
- Like sign channels with WW.